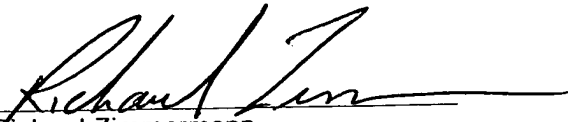


SOLE INVENTOR

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Richard Zimmermann

**APPLICATION FOR
UNITED STATES LETTERS PATENT**

S P E C I F I C A T I O N

TO ALL WHOM IT MAY CONCERN:

Be it known that I, Mats A. Brenner, a citizen of Sweden,
residing at 4275 Deerwood Lane, in the County of Hennepin and State of
Minnesota have invented a new and useful **APPARATUS FOR NAVIGATION
SATELLITE SIGNAL QUALITY MONITORING**, of which the following is a
specification.

APPARATUS FOR NAVIGATION SATELLITE SIGNAL QUALITY MONITORING

Technical Field of the Invention

5 The present invention relates generally to
satellite based positioning systems such as the Global
Positioning System (GPS) and more particularly to the
monitoring of the quality of the signals transmitted by
satellites in a satellite based positioning system.

Background of the Invention and Prior Art

10 A satellite based positioning system is used
to determine a position of a receiver and typically
includes satellite control facilities, a plurality of
satellites, the receiver, and one or more local or
regional ground stations. Each of the satellites
15 transmits a signal that contains a code and certain
prescribed information useful to the receiver in
determining its position. The receiver synchronizes
itself to the codes of at least four satellites and uses
the information in the signals from these satellites in
20 order to perform a triangulation like procedure so as to
determine its coordinates and time offset with respect to
a reference, such as the center of the Earth and the GPS
standard time.

The receiver is not constrained to a specific location and, therefore, represents a variable position. Indeed, the purpose of the satellite based positioning system is to make it possible for the receiver to
5 determine its position regardless of the location of the receiver. On the other hand, the local or regional ground station is in a fixed location and is used to monitor the signals transmitted by the satellites. The signals transmitted by the satellites can be adversely
10 affected, for example, by atmospheric conditions which can lead to improper position determinations by the receiver. The ground station, therefore, notifies the receiver of any necessary signal corrections to allow the receiver to make more accurate position calculations.
15 This arrangement is referred to as differential positioning.

The ground station of the present invention also monitors the signals transmitted by the satellites in order to detect faults within the satellites. For
20 GPS, these faults are specified by the FAA who imposes stringent requirements to protect users against positioning system signal faults. A set of test waveforms has been chosen by the FAA to represent at least some of the more egregious faults. These waveforms

are used for certification testing of the ground station equipment.

The prior art determines faults by comparing conventional code tracking discriminators at different correlator spacings. As shown in Figure 1, a correlation curve is established by correlating the code received from a satellite with a suite of code references which are time shifted replicas of the code transmitted by that satellite. For example, seven correlation measurements may be calculated as shown in Figure 1. The in-phase measurement IP represents the amount of correlation between the received code and a reference code that has a zero time shift with respect to the received code (this measurement is referred to as punctual). The in-phase measurement IE_1 represents the amount of correlation between the received code and a reference code that has a first predetermined time shift so that it is early with respect to the received code. The in-phase measurement IL_1 represents the amount of correlation between the received code and a reference code that has a second predetermined time shift so that it is late with respect to the received code. Similarly, the in-phase measurement IE_2 is derived using a third predetermined time shift, the in-phase measurement IL_2 is derived using

a fourth predetermined time shift, the in-phase measurement IE_3 is derived using a fifth predetermined time shift, and the in-phase measurement IL_3 is derived using a sixth predetermined time shift. The magnitude of
5 the first predetermined time shift may be equal to the magnitude of the second predetermined time shift, the magnitude of the third predetermined time shift may be equal to the magnitude of the fourth predetermined time shift, and the magnitude of the fifth predetermined time
10 shift may be equal to the magnitude of the sixth predetermined time shift. It is assumed that all measurements are normalized such that the measured correlation is a function of the time shifts only and not the absolute power of the received satellite signal.

15 First, second, and third discriminators are then formed according to the following equations:

$$d_1 = (IL_1 - IE_1) IP$$

$$d_2 = (IL_2 - IE_2) IP$$

$$d_3 = (IL_3 - IE_3) IP$$

These discriminators are thereafter compared to each other through the formation of quantities $d_{1,2}$, $d_{1,3}$, and $d_{2,3}$ according to the following equations:

$$d_{1,2} = |d_1 - d_2|$$

5

$$d_{1,3} = |d_1 - d_3|$$

$$d_{2,3} = |d_2 - d_3|$$

The quantities $d_{1,2}$, $d_{1,3}$, and $d_{2,3}$ are compared to corresponding thresholds $D_{1,2}$, $D_{1,3}$, and $D_{2,3}$ such that, if the first discriminator $d_{1,2}$ exceeds $D_{1,2}$, if the second
10 discriminator $d_{1,3}$ exceeds $D_{1,3}$, or if the third discriminator $d_{2,3}$ exceeds $D_{2,3}$, a fault is assumed to exist. During normal operation of the global positioning system, this test is performed on the signals received from each of the satellites. During certification, a
15 test is to be performed using each of the test waveforms chosen by the FAA in order to prove that fault detection occurs.

At least one of the problems with this method is that it requires six correlators in order to
20 determine the three quantities $d_{1,2}$, $d_{1,3}$, and $d_{2,3}$ which is

too much hardware for the amount of useful data being provided.

It is also known for ground stations to determine faults by scanning the whole correlation peak (i.e., the portion of the correlation curve around the
5 punctual in-phase measurement IP) in order to determine whether the peak varies from some prescribed norm by a predetermined amount. However, this fault detection arrangement requires a substantial amount of computing
10 power and it lacks accuracy.

A third method in the prior art uses the following ratios between the measurements IE3, IE2, IE1, IL1, IL2, and IL3:

$$r_{E3,E2} = \frac{IE3}{IE2}$$

15

$$r_{E3,E1} = \frac{IE3}{IE1}$$

$$r_{E3,L1} = \frac{IE3}{IL1}$$

.
.
.

Each of these ratios is compared to a corresponding predetermined value.

The present invention is directed to an arrangement which overcomes one or more problems of the prior art.

Summary of the Invention

In accordance with one aspect of the present invention, an apparatus for the detection of positioning system satellite signal faults comprises a correlator and a fault detector. The correlator determines a plurality of correlation measurements at points along a correlation curve, and each correlation measurement is based upon a correlation between a received satellite signal and a reference. The fault detector determines differences between the correlation measurements along the correlation curve and detects a fault from the differences.

In accordance with another aspect of the present invention, a method of detecting faults affecting a signal transmitted by a positioning system satellite comprises: correlating the transmitted signal with a first reference in order to determine a first correlation measurement at a first point along a correlation curve;

correlating the transmitted signal with a second
reference in order to determine a second correlation
measurement at a second point along the correlation
curve; correlating the transmitted signal with a third
5 reference in order to determine a third correlation
measurement at a third point along the correlation curve;
determining a first difference from the first and second
correlation measurements; determining a second
difference from the second and third correlation
10 measurements; directly comparing the first difference to
a first threshold; directly comparing the second
difference to a second threshold; and, detecting a fault
in the satellite based upon the comparisons of the first
and second differences to the first and second
15 thresholds.

In accordance with still another aspect of the
present invention, a method of detecting faults affecting
a signal transmitted by a positioning system satellite
comprises: correlating the transmitted signal with
20 references in order to determine a plurality of
correlation measurements at corresponding points along a
correlation curve; determining a single value from n
pairs of the correlation measurements, wherein $n > 2$;
comparing the single value to a threshold; and,

detecting a fault in the satellite based upon the comparison.

Brief Description of the Drawings

These and other features and advantages will
5 become more apparent from a detailed consideration of the invention when taken in conjunction with the drawings in which:

Figure 1 is a waveform showing a correlation
diagram useful in explaining prior art fault detection as
10 implemented in a ground station in a global positioning system;

Figure 2 is a schematic diagram of a portion
of a ground station receiver pertinent to the present
invention; and,

15 Figure 3 is a waveform showing a correlation diagram useful in explaining fault detection as implemented by a ground station in a global positioning system in accordance with the present invention.

Detailed Description

20 A portion of a ground station 10 pertinent to the present invention is shown in Figure 2. The ground station has correlators 12-E_m, . . . , 12-E₃, 12-E₂, 12-E₁,

12-P, 12-L₁, 12-L₂, 12-L₃, . . . , 12-L_n, where n + m is greater than two, and where n is the number of late correlation measurements and m is the number of early correlation measurements to be used in determining a fault. The correlator 12-P correlates the usual code in the received signal with a reference 14-P to produce a punctual correlation output IP, the correlator 12-L₁, correlates the code in the received signal with a reference 14-L₁ to produce a late correlation output IL₁, the correlator 12-L₂ correlates the code in the received signal with a reference 14-L₂ to produce a late correlation output IL₂, the correlator 12-L₃ correlates the code in the received signal with a reference 14-L₃ to produce a late correlation output IL₃, . . . , and the correlator 12-L_n correlates the code in the received signal with a reference 14-L_n to produce a late correlation output IL_n.

In addition, a correlator 12-E₁ correlates the code in the received signal with a reference 14-E₁ to produce an early correlation output IE₁, a correlator 12-E₂ correlates the code in the received signal with a reference 14-E₂ to produce an early correlation output IE₂, a correlator 12-E₃ correlates the code in the received signal with a reference 14-E₃ to produce an

early correlation output IE_3, \dots , and a correlator 12-
 E_m correlates the code in the received signal with a
reference 14- E_m to produce an early correlation output
 IE_m .

5 The ground station 10 has a processor 16 which
uses the punctual and late correlation outputs $IP, IL_1,$
 IL_2, IL_3, \dots, IL_n as disclosed hereinafter in order to
determined whether a fault exists. Alternatively or
10 additionally, the processor 16 can use the early
correlation outputs $IE_1, IE_2, IE_3, \dots, IE_m$ as disclosed
hereinafter in order to determined whether a fault
exists.

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15 In order to generate the punctual correlation
output IP , the processor 16 shifts the reference 14- P ,
which may be a replica of the code contained in the
received signal, until an optimum correlation is
obtained. The processor 16 then controls the reference
14- L_1 so that the reference 14- L_1 is a replica of the
reference 14- P and so that the reference 14- L_1 is time
20 shifted with respect to the reference 14- P by a first
predetermined amount of time. Accordingly, the
correlator 12- L_1 produces the late correlation output IL_1 .
The processor 16 also controls the reference 14- L_2 so
that the reference 14- L_2 is a replica of the reference

14-P and so that the reference 14-L₂ is time shifted with respect to the reference 14-P by a second predetermined amount of time, where the second predetermined amount of time is greater than the first predetermined amount of
5 time. Accordingly, the correlator 12-L₂ produces the late correlation output IL₂. Similarly, the processor 16 controls the reference 14-L₃ so that the reference 14-L₃ is a replica of the reference 14-P and so that the reference 14-L₃ is time shifted with respect to the
10 reference 14-P by a third predetermined amount of time, where the third predetermined amount of time is greater than the first and second predetermined amounts of time. Accordingly, the correlator 12-L₃ produces the late correlation output IL₃. The remaining late correlation
15 outputs up to IL_n are generated in a like manner. The first, second, third, etc. predetermined amounts of time are all chosen so that the late correlation outputs IL₁ through IL_n are all on the downward or late slope of the correlation curve as shown in Figure 3.

20 Additionally or alternatively, the correlators 12-E₁, 12-E₂, 12-E₃, . . . , 12-E_m may be positioned so as to generate the early correlation outputs IE₁, IE₂, IE₃, . . . , IE_m. Also, quadrature phase correlation outputs QE_m, . . . , QE₁, QP, QL₁, . . . , QL_n may be generated by

correlating the code in the received signal to a time shifted quadrature form of the reference 14-P. In accordance with this latter alternative, each measurement used to generate a fault indication may be formed as an
5 RMS (Root Mean Square) value of the corresponding in phase and quadrature phase measurements.

The set $IE_m, \dots, IE_3, IE_2, IE_1, IP, IL_1, IL_2, IL_3, \dots, IL_n$ may be denoted as $I_m, \dots, I_{-3}, I_{-2}, I_{-1}, I_0, I_1, I_2, I_3, \dots, I_n$ and the following
10 corresponding set of RMS values

$$\sqrt{IE_m^2 + QE_m^2}, \dots, \sqrt{IE_1^2 + QE_1^2}, \sqrt{IP^2 + QP^2}, \dots, \sqrt{IL_n^2 + QL_n^2}$$

may be denoted as $R_m, \dots, R_{-3}, R_{-2}, R_{-1}, R_0, R_1, R_2, R_3, \dots, R_n$.

If early as well as late correlation outputs
15 are to be used for fault detection, the processor 16 processes the early correlation outputs IE_m through IE_1 , the punctual correlation output IP , and/or the late correlation outputs IL_1 through IL_n so as to derive one or more measured differences $d_{i,j}$. These measured
20 differences $d_{i,j}$ are generated in accordance with the following equations:

$$d_{i,j} = I_i - I_j \quad (1)$$

or

$$d_{i,j} = R_i - R_j \quad (2)$$

5 where $i = -m, \dots, n$ and $j = -m, \dots, n$, and where
the negative sign indicates measurements on the early
slope and the positive sign indicates measurements on the
late slope of the correlation curve.

10 At this point, it is possible to subtract the
expected difference from all or a subset of these
measured differences $d_{i,j}$ and to compare the resulting
difference deviations to corresponding thresholds in
order to determine the existence of a fault. For
example, assuming that all of these difference deviations
15 are used, then these difference deviations may be
compared to corresponding thresholds in accordance with
the following equation:

$$|d_{i,j} - Ed_{i,j}| > D_{i,j} \quad (3)$$

where $Ed_{i,j}$ is the difference that is expected for each corresponding measured difference $d_{i,j}$ when there is no fault.

In some cases, the measured differences $d_{i,j}$ may be affected by thermal and multipath noise which could lead to false detection of faults, depending upon the sensitivity of the fault detection apparatus, i.e., the magnitudes of the thresholds $D_{i,j}$. Accordingly, in these cases, a fault could be detected when no fault is in fact present, or a fault which is present might not be detected at all.

The thermal noise content in $d_{i,j}$ can be determined as a function of the delay $h_{i,j}$ between the reference codes 14- E_m , . . . , 14- E_3 , 14- E_2 , 14- E_1 , 14- P , 14- L_1 , 14- L_2 , 14- L_3 , . . . , 14- L_n . The delay $h_{i,j}$ is the delay between the two references that are correlated with the received signal to produce I_i and I_j . Typically, $h_{i,j} = 0.025$ to 0.05 chip, but may vary from this range. The thermal noise $th1$ in $d_{i,j}$ depends on the signal to noise ratio and the standard deviation (1-sigma) of $th1$ and is given by the following equation:

$$\sigma_{th1}(i,j) = 293 \sqrt{\frac{h_{i,j}B}{S/No}} \quad (4)$$

where B is the two-sided bandwidth of the noise. In addition, there is another contribution, th_2 , to the thermal noise due to the variation of the punctual reference (i.e., the reference 14-P). Accordingly, the
5 total thermal noise is $th = th_1 + th_2$. The multipath noise mp depends on the antenna gain pattern and its overbounding 1-sigma $\sigma_{mp}(i,j)('e')$ is expressed as a function of satellite elevation $'e'$. The statistical properties of th and mp are usually identified at
10 installation of the ground station and the statistical information is parameterized and are thereafter stored in memory.

One way to minimize any adverse effects of thermal and multipath noise is to make a plurality of
15 measurements for each of the measured differences $d_{i,j}$ that are used in the detection of faults. Then, the measurements for each of the measured differences $d_{i,j}$ may be averaged or filtered. Because the thermal noise and some of the multipath noise are not particularly
20 correlated from one measurement to the next, averaging will tend to reduce the effects of thermal and multipath noise.

As an example, let it be assumed that the punctual correlation output IP and the late correlation

outputs IL_1 and IL_2 are used to detect faults.

Accordingly, the following measured differences are determined: $d_{0,1} = IP - IL_1$; $d_{0,2} = IP - IL_2$; and, $d_{1,2} = IL_1 - IL_2$. In order to reduce the effects of thermal and

5 multipath noise, however, plural calculations of the measured difference $d_{0,1}$ are made based upon plural correlation measurements resulting in plural punctual correlation outputs IP and plural late correlation outputs IL_1 . All such calculations of the measured

10 difference $d_{0,1}$ are then averaged. Similarly, plural calculations of the measured difference $d_{0,2}$ are made based upon the plural correlation measurements resulting in plural punctual correlation outputs IP and plural late correlation outputs IL_2 . As before, all such

15 calculations of the measured difference $d_{0,2}$ are averaged. Likewise, plural calculations of the measured difference $d_{1,2}$ are made based upon the plural correlation

measurements resulting in the plural late correlation outputs IL_1 and plural late correlation outputs IL_2 .

20 Again, all such calculations of the measured difference $d_{1,2}$ are averaged. These averages may then be compared to their corresponding thresholds $D_{0,1}$, $D_{0,2}$, and $D_{1,2}$ in order to determine the existence of a fault.

Another way to reduce the effect of thermal and multipath noise is to suitably filter the measured differences $d_{i,j}$, or the punctual correlation output IP, the late correlation outputs IL_1 through IL_n , and the
5 early correlation outputs IE_1 through IE_m , such as with a low pass filter.

Still another way to reduce the effect of thermal and multipath noise is by implementing the following procedure. In describing this procedure, it is
10 useful to define a covariance matrix P in accordance with the following equation:

$$P = E[(\underline{d} - \underline{m})(\underline{d} - \underline{m})^T] \quad (5)$$

where the underlines indicate vectors, where $E[A]$ is the statistical expectation of A , where the vector \underline{m} is the
15 mean value of the vector \underline{d} , and where the vector \underline{d} is determined in accordance with the following equation:

$$\underline{d}^T = (d_1, d_2, d_3, d_4, \dots, d_N) \quad (6)$$

where $d_k = I_k - I_{k-1} - Ed_k$ for $k = -m, \dots, n-1$ or where
 $d_k = R_k - R_{k-1} - Ed_k$ for $k = -m, \dots, n-1$ assuming $N + 1$
20 correlation measurements such as $I_m, \dots, I_{-3}, I_{-2}, I_{-1},$

$I_0, I_1, I_2, I_3, \dots, I_n$. An upper triangular matrix U and a diagonal matrix D are determined according to the following equation:

$$P = UDU^T \quad (7)$$

5 where P is the covariance matrix given by equation (6).
With the covariance matrix P known from equation (6), the
upper triangular matrix U and the diagonal matrix D can
be determined, for example, by using Cholesky
factorization. Thus, the following relationship may be
10 defined in accordance with the following equation:

$$\tilde{\underline{d}} = U^{-1}(\underline{d} - \underline{m}) \quad (8)$$

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where $\tilde{\underline{d}}$ is a vector representing the decorrelated
deviations generating the vector \underline{d} . Equation (9) can be
re-written according to the following equation:

15

$$\underline{d} = U \tilde{\underline{d}} + \underline{m} \quad (9)$$

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Then, combining equations (6) and (10) produces the
following equation:

$$P = E [U \tilde{\underline{d}} (U \tilde{\underline{d}})^T] = U E [\tilde{\underline{d}} (\tilde{\underline{d}})^T] U^T \quad (10)$$

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By comparing equations (6) and (11), it can be seen that D is given by following equation:

$$D = E [\tilde{\underline{d}} (\tilde{\underline{d}})^T] \quad (11)$$

5 and that D, as defined above, is a diagonal matrix having the following format:

$$D = \begin{bmatrix} \tilde{\sigma} & 0 & 0 & \dots & 0 \\ 0 & \tilde{\sigma} & 0 & \dots & 0 \\ 0 & 0 & \tilde{\sigma} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & \tilde{\sigma} \end{bmatrix} \quad (12)$$

Variances $\tilde{\sigma}_i^2$ are then determined from the diagonal matrix D. As can be seen from the above equations, the

10 deviations in the vector $\tilde{\underline{d}}$, where i varies from 1 to N are uncorrelated and have the variances $\tilde{\sigma}_i^2$.

The final χ^2 value for determining a fault is obtained according to the following equation:

$$d[\chi^2] = \sum_{i=1}^n \frac{\tilde{d}_i^2}{\tilde{\sigma}_i^2} \quad (13)$$

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A normalization to $\sigma = 1$ as required in the definition of χ^2 will be performed in equation (14). The value $d[\chi^2]$ is a single value which has reduced thermal and multipath noise, which represents information regarding a plurality of correlation measurements, and which may be compared to a threshold D in order to determine the existence of a fault.

Certain modifications of the present invention have been discussed above. Other modifications will occur to those practicing in the art of the present invention. For example, as described above, the χ^2 distribution is based on the assumption that all involved distributions are Gaussian. The distributions of d_k may deviate from this assumption and appropriate corrections to the formulas given here may be necessary.

Moreover, the present invention has been described above in connection with the detection of satellite signal faults such as those specified by the

FAA. These faults result in signal distortions detectable by use of the present invention. The present invention as embodied by the following claims can also be used to detect other signal distortions such as those
5 arising from multipath and satellite code cross correlation effects.

Accordingly, the description of the present invention is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the
10 best mode of carrying out the invention. The details may be varied substantially without departing from the spirit of the invention, and the exclusive use of all modifications which are within the scope of the appended claims is reserved.